Frederic Herold & Associates, Inc.

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To: L. Ambrose/Code 532.2

From: Fredrick Herold & Associates, Inc.

Subject: Final Report

Attached is the Final Report for the STGT Return Data Delay task.

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STGT RETURN DATA DELAY
FINAL REPORT

November 30, 1995

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SUMMARY

A discrepancy in the results of spacecraft clock correlation was observed over approximately a one year period by TDRSS Users who alternated between the use of WSGT and the use of STGT. In particular, Tropical Ocean Mapping Experiment (TOPEX), which normally implements the return data delay (RDD) technique of clock correlation, reported approximately a 60 µs difference in their clock, depending on which ground station was used. Compton Gamma Ray Observatory (CGRO), using the User Spacecraft Clock Calibration System (USCCS), did not incur this problem.

Fredrick Herold & Associates, Inc. (FH&A) has undertaken an in-depth analysis and test program in support of Code 532.2 to understand the cause of this discrepancy. The delay through the test modulator in the Performance Measuring and Monitoring System (PMMS) Test Equipment (PTE), which is used to calibrate the STGT time delay, has different values that depend on whether or not convolutional encoding is used. This analysis and test effort has determined that the incorrect delay value had been used for the station calibration. In addition, an extensive delay calibration of the integrated receiver (IR) contained incorrect values, possibly also caused by the use of an incorrect PTE delay.

A very good approximation for the correct STGT delay value contained in the OPM52 message is given by the following:

MA: $T_{rdd} = 102.8T_b + 60\ \mu s$

SSA: $T_{rdd} = 103.8T_b + 6\ \mu s$

where T_{rdd} is the delay value and T_b is the time of one data bit period or $(\text{data rate})^{-1}$.

1.0 BACKGROUND

Return data delay (RDD) of a ground station, in this case the STGT, is needed by science spacecraft Project Operations Control Center (POCC) personnel for setting their onboard clock. RDD is the signal delay of the station from the space-ground link (SGL) antenna's range reference point to the multiplexer/demultiplexer (MDM), where a Universal Time Coordinated (UTC) time tag is placed on the data stream.

Ever since initial operational capability (IOC) of STGT, the Tropical Ocean Mapping Experiment (TOPEX) Project had stated that there was an apparent jump in their spacecraft clock when the STGT was used for time calibration, as compared to when WSGT was used for that purpose. In support of L. Ambrose and D. Daughtridge (Code 532.2), Fredrick Herold & Associates, Inc. (FH&A) investigated the problem and found that TOPEX and other projects would not have a clock calibration problem at STGT if the ground station delay reported in the OPM 52 (referred to as OPM 62 by the Network Control Center (NCC)) were smaller by the time of one data bit period, T_b. Measurements of the STGT data delay using GSFC-generated data resulted in the same delay reported in the OPM, but the measurements relied on an STGT calibration similar to the calibration used to generate the OPM 52 values. This led to the need for determining if the STGT delay was, in fact, correct and if an incorrect WSGT delay had been used all this time. Evaluation of this data and previous spacecraft time calibration data that included comparison to the Global Positioning System (GPS) (TOPEX and X-Ray Timing Explorer (XTE)) and astronomical data from pulsars (CGRO) indicated that previous calibration using the WSGT was correct. We proposed that either the STGT MDM was time tagging too late by one data bit period or the calibration of the Performance Measuring & Monitoring System (PMMS) Test Equipment (PTE) was incorrect. The MDM performance was confirmed by Lockheed Martin to be correct, leaving calibration of the PTE Test Modem as the likely suspect.

2.0 ANALYSIS OF EQUIPMENT DELAYS

2.1 PMMS Test Equipment Calibration

The calibration of the PTE was described in PTE Test Modem Program Information Release (PIR) 713T-E4-5520-1262 dated 27 August 93 and an associated memo from J. Henry (STGT) dated 29 October 93, both of which FH&A received about July 1995. These documents showed the Test Modem delay to be $5T_b$ when the convolutional coding was turned off and $6T_b$ when convolutional coding was turned on. These delays were confirmed by direct measurement during the week of 14 August 95. Upon further investigation it was determined that when the return receive equipment delay was characterized (Figure 1), the $5T_b$ uncoded Test Modem delay value was subtracted from the round trip (i.e., from data generation through modulation to demodulation) coded measurement rather than the $6T_b$ coded value, resulting in a value of equipment delay that was $1T_b$ too large. This error resulted in a database value for station RDD that was, therefore, $1T_b$ too large. Note that Figures 1-5 show the delays as they are now understood. Originally, both the Test Modem and the Integrated Receiver (IR) delays were incorrect. It should also be noted that the above PTE Test Modulator delays apply to the use of an input port that corresponds to STGT internal testing. When used for a GSFC end-to-end RDD test (Figures 2, 3, and 4), data enters the Test Modem through a different port. In this situation, the delay is approximately $2T_b$ less than for the STGT internal calibration situation. Thus, for the purposes of these measurements, the test modem delay has now been established to be $3.9T_b$ (for coded data) rather than the $2.9T_b$ value that was previously reported. This $1T_b$ difference results in a correct station delay when using the GSFC measurement method.

2.2 Integrated Receiver Delay

An effort was made to examine the IR delay. It had been reported at each data rate as some number of microseconds equivalent to $102.8T_b$; however, the end-to-end measurements with the Automated Data Processing Equipment (ADPE) Simulation Program (ASP) using the correct PTE delay indicated it should have been $101.8T_b$ (Figure 5). An extensive analysis of the IR delay had been performed prior to May

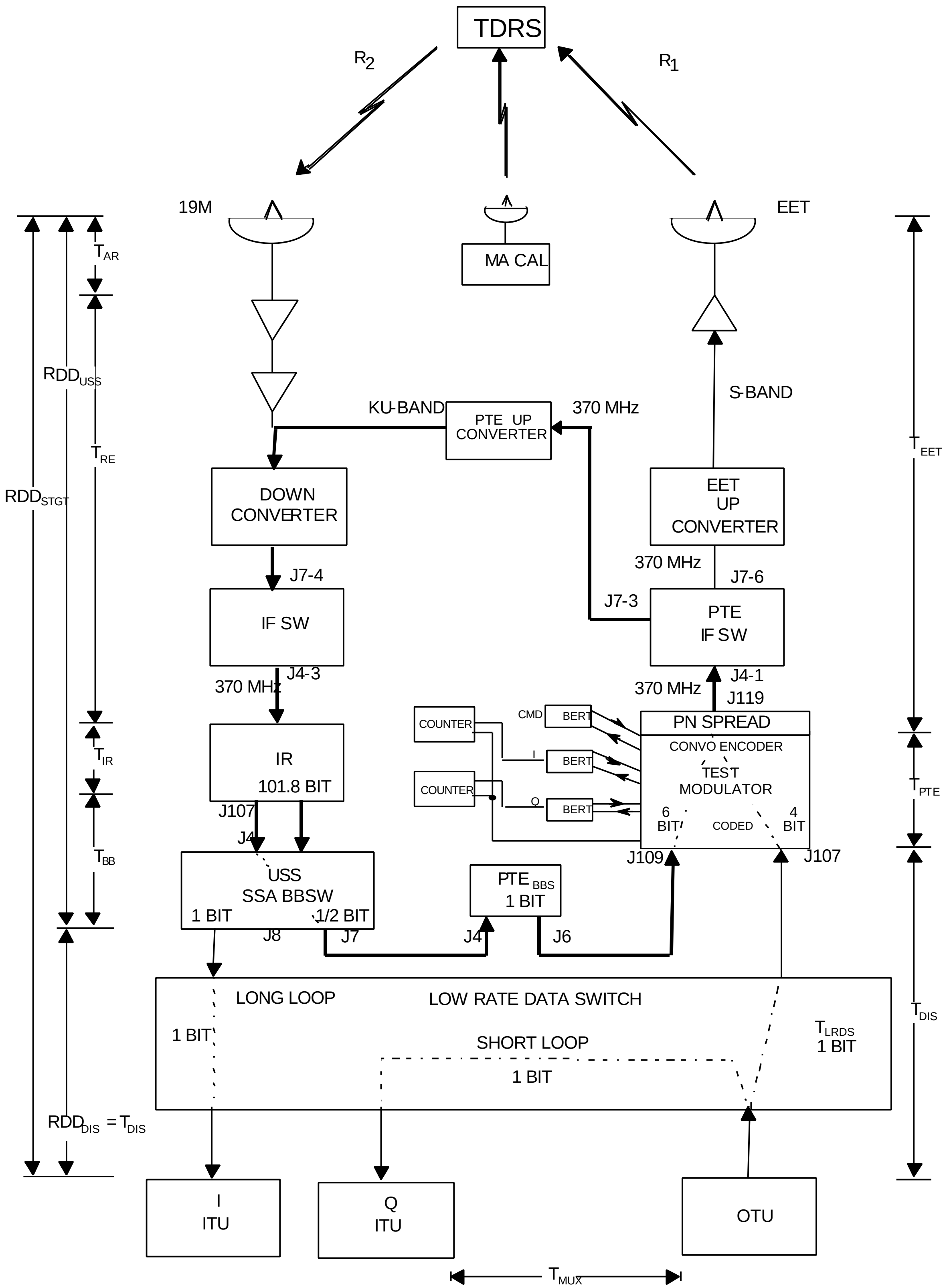

Figure 1. PTE Loop Pre-Service Test

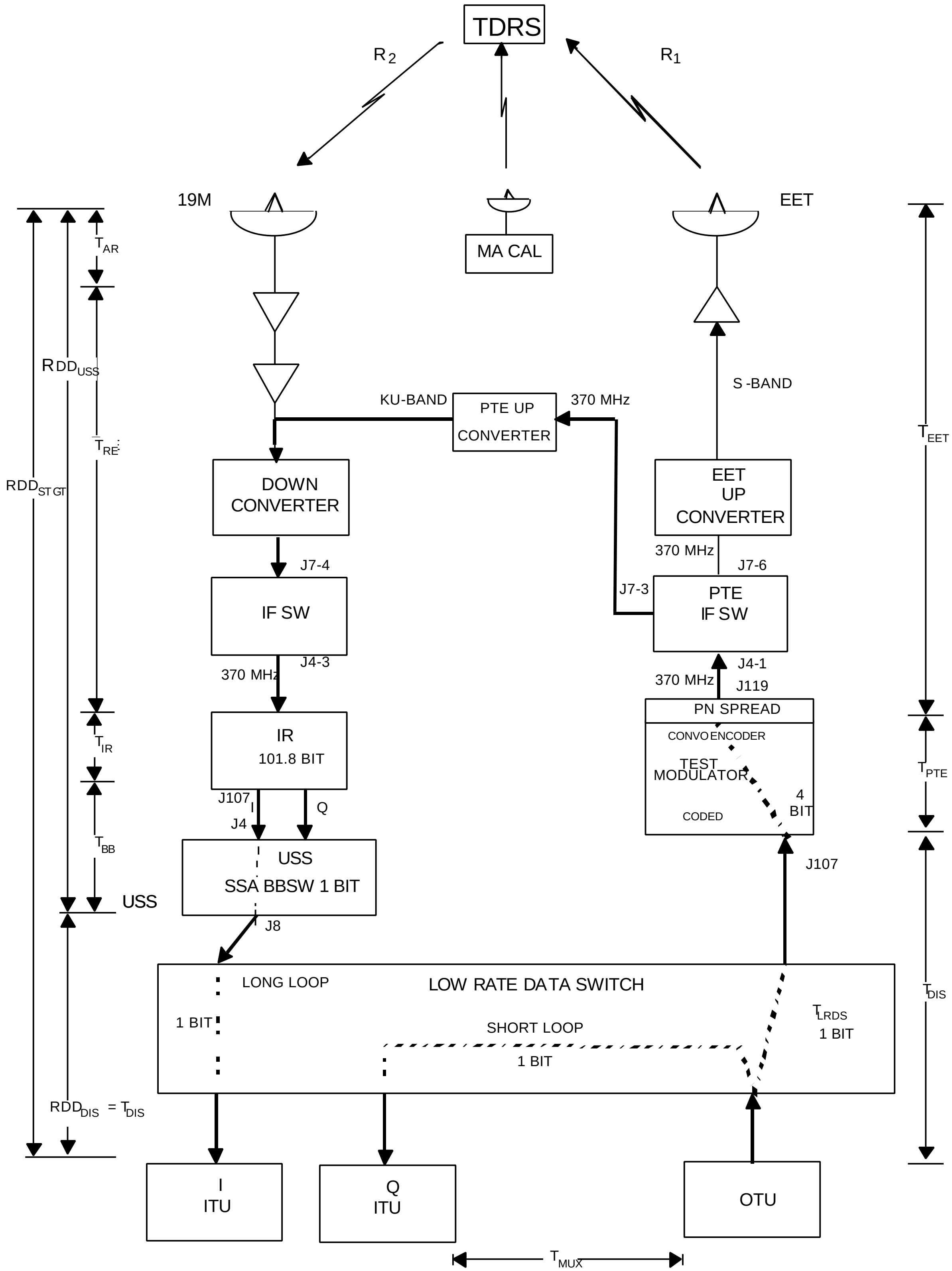

Figure 2. GSFC RDD Test - SSA EET Using Medium Loop

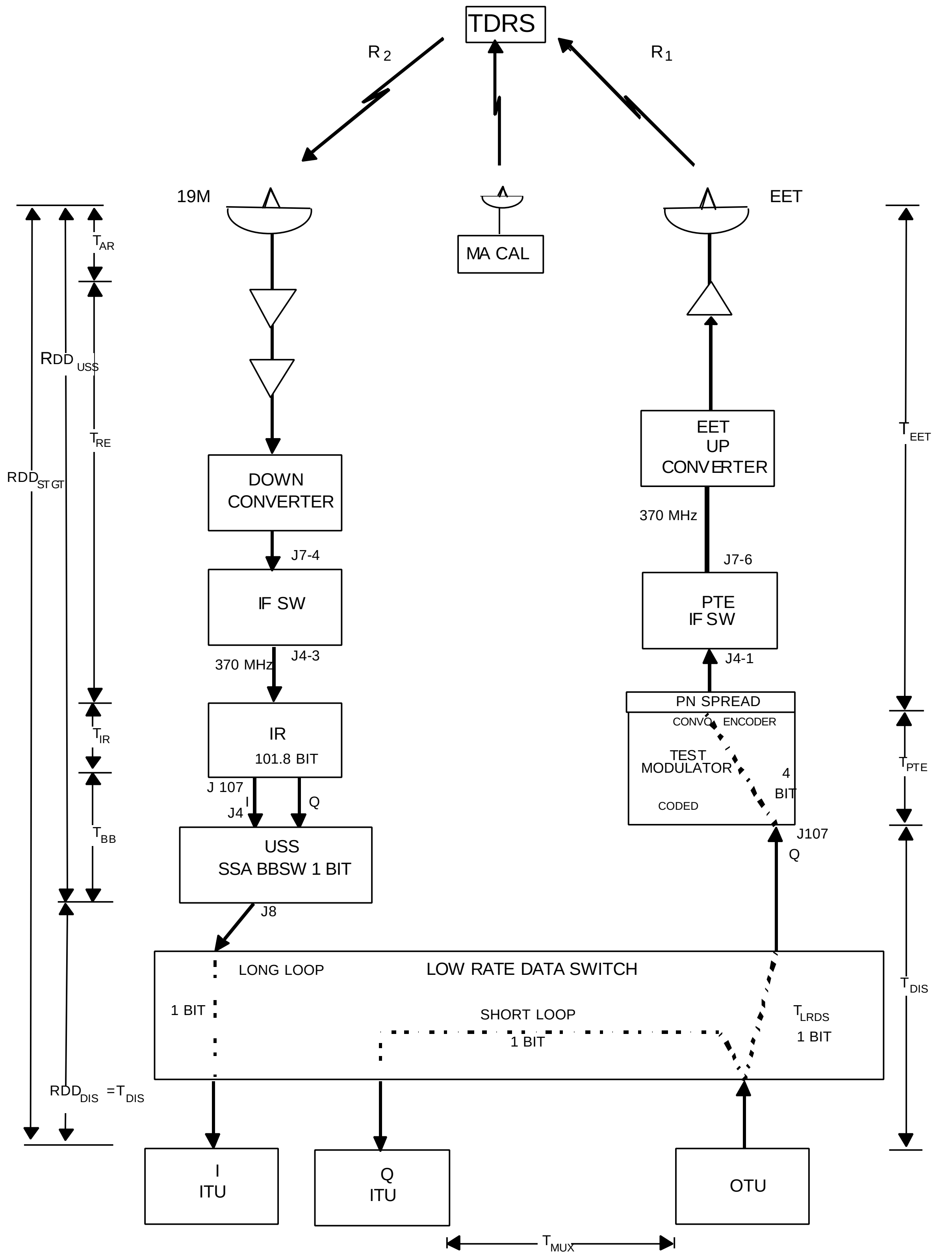

Figure 3. GSFC End-to-End RDD Test - SSA Through TDRS

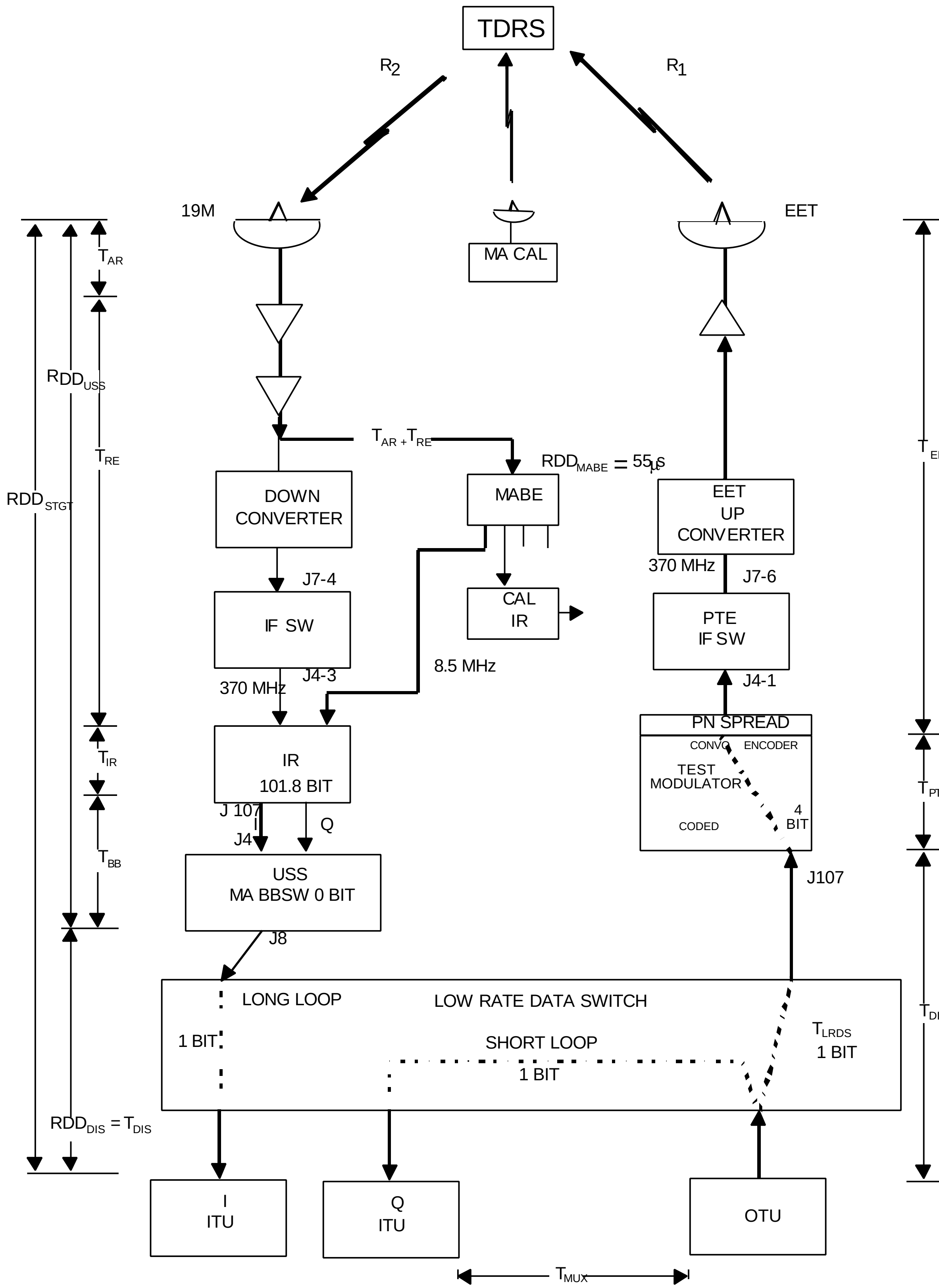

Figure 4. GSFC End-to-End RDD Test - MA Through TDRS

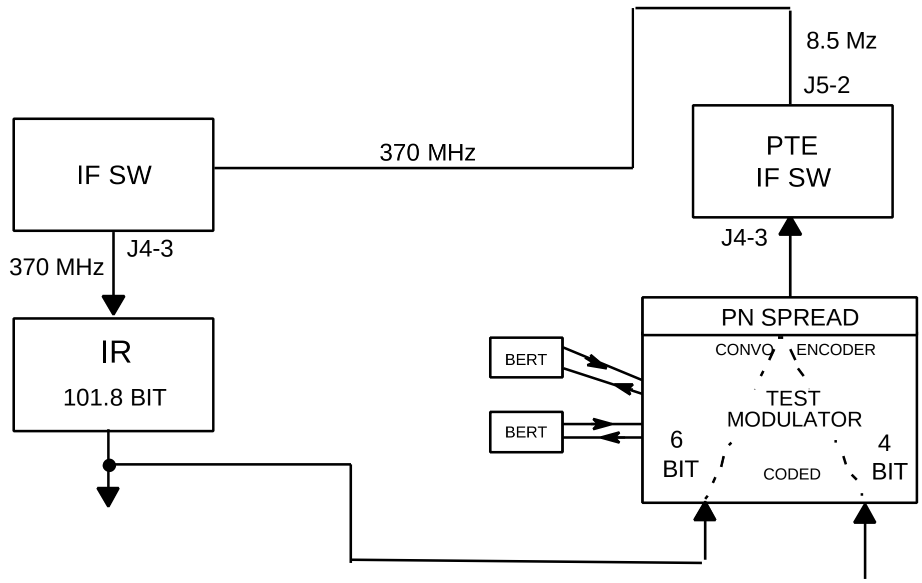

Figure 5. ASP Test Loop Used to Measure IR Delay

1994 and was included in an 18 May 94 PIR (STGT-SE-231) by S. Wozniak (STGT/Lockheed Martin). The PIR generated the database model which was used to calculate the OPM 52 values, and it allegedly proved that the IR delay analysis which resulted in the $102.8T_b$ delay had at least a 99% confidence level. This high confidence level and the extensiveness of the analysis, together with the fact that Qualcomm documents describing the Q1650 Viterbi decoder integrated circuit in the IR claimed that the decoder delay was $102.5T_b$, had made the reported $102.8T_b$ delay value seem reasonable.

However, after being questioned by F. Hartman (GTE) and FH&A personnel for details which were unclear in their documents, Qualcomm acknowledged that the decoder delay was actually $102.5T_b$ **$\pm$ $4T_b$** and variable, depending on synchronization history. If, in fact, the decoder delay were $98.5T_b$ (i.e., $102.5T_b$ - $4T_b$), adding $3T_b$ of delay for the IR output processor (per F. Hartman analysis) and another ~$0.6T_b$ delay for the pseudonoise despreader (per FH&A analysis of the Wozniak PIR) yields a total of $102.1T_b$ for the IR delay. This value is very close to the $101.8T_b$ value indicated by the end-to-end measurements. Thus, the consensus was that the extensive PIR delay and error analysis could be ignored.

3.0 RETURN DATA DELAY MEASUREMENTS

3.1 Return Data Delay Calculation

The measured delay, T_{meas}, consists of the actual station delay, T_{rdd}, plus PTE delay, T_{pte}, and range propagation delay, T_{rng}, as shown in Figures 3 and 4 and the following equation:

$$T_{meas} = T_{rdd} + T_{pte} + T_{rng} \tag{1}$$

Additional delays through TDRS and other end-to-end test (EET) equipment are negligible. Rewriting this equation then yields an equation for station RDD:

$$T_{rdd} = T_{meas} - T_{pte} - T_{rng} \tag{2}$$

The PTE delay, when used in a GSFC end-to-end RDD test configuration, has been established to have a delay of 3.9 data bit periods; that is,

$$T_{pte} = N_{pte} \cdot T_b \tag{3}$$

where $N_{pte} = 3.9$

The station RDD can be thought of as having two components: a portion caused by data clocking (NT_b) and a propagation portion (T_{rf}); thus,

$$T_{rdd} = NT_b + T_{rf} \tag{4}$$

The measured delay can then be written as follows:

$$T_{meas} = (NT_b + T_{rf}) + T_{pte} + T_{rng} \tag{5}$$

Applying this equation to two separate measurements, each at a different data rate, yields the following equations for N and T_{rf}:

$$N = \frac{(T_{meas1} - T_{rng1}) - (T_{meas2} - T_{rng2})}{T_{b1} - T_{b2}} - N_{pte} \tag{6}$$

$$T_{rf} = \frac{T_{b1}(T_{meas2}-T_{rng2}) - T_{b2}(T_{meas1}-T_{rng1})}{T_{b1} - T_{b2}} \qquad (7)$$

3.2 GSFC End-to-End Test Methodology

Data is generated at the Simulation Operations Center (SOC) and sent to STGT via Nascom. There it is split at the Low Rate Data Switch into two streams (Figures 2, 3, and 4). One stream is routed back to the MDM. The other is modulated by the PTE Test Modulator, upconverted and transmitted to TDRS by the EET equipment, received and demodulated by the SGLT return equipment, and routed to the MDM. Both streams (called "short loop" and "long loop", respectively) are time tagged by the MDM and sent via Nascom back to the SOC. The delay of the “long” loop through the baseband switch is not factored into this equation because it is canceled out by the “short” loop delay in its own path to the MDM.

The differences between the MDM time tags are evaluated by SOC delogging software. From these differences the PTE delay and range propagation delay are subtracted, yielding a measured value for station RDD, per Eq. (2). The range propagation delays are provided by STGT personnel, who obtain the information from delogged MA calibration data.

In these tests the SOC generated a CGRO-like data pattern with 64 1024-bit minor frames in each major frame and a 32-bit synchronization marker included in each minor frame. Any standard PN communication test pattern could be used as the data, however, as long as its length is at least as great as the bit period delay that is being evaluated. Since the station delay at STGT is on the order of $103T_b$ - $104T_b$, a 127-bit length pattern (2^7-1) would suffice. As a frame synch marker, 32 bits would be used starting from the portion of the pattern that has the largest number of “ones” in a row, which for the 127-bit pattern is FE041851 (hex).

3.3 Measurement Results

Table 1 contains the results of the 17 August 95 STGT RDD measurements. The column marked "?" is the difference between the measured delay value and that provided at that time by the OPM 52 message. Except for the 8 kbps MA measurement, the differences were consistently (approximately) one bit period. This verified the database error described above. There is no explanation as yet for the approximately half bit period discrepancy at 8 kbps.

Table 1. STGT RDD Measurements (8/17/95)

Event No.	Service	Rate (kbps)	Tb (µs)	Tmeas (µs)	Trng (µs)	Tpte (µs)	Trdd (µs)	OPM 52 (µs)	? (Tb)
1	MA	8 (Dual)	125	282691	269351	487	12852	13032	1.4
2	MA	16 (Dual)	62.5	276068	269339	244	6485	6544	0.9
3	MA	32 (Dual)	31.25	272729	269334	122	3273	3300	0.9
4	MA	16 (Single*)	62.5	276061	269331	244	6486	6544	0.9
5	SSA	16 (Dual)	62.5	276080	269342	244	6494	6553	0.9

* pre-detection combining

Applying the data from Event Nos. 3 and 4 to Eqs. (6) and (7) yields the following values for N and T_{rf} for the MA case:

$$N = 102.8$$
$$T_{rf} = 60\ \mu s$$

Thus, the approximation for STGT MA RDD can be written as follows:

$$T_{rdd}\ (MA) = 102.8T_b + 60\ \mu s \quad (8)$$

For data rates of 16 kbps and 32 kbps (bit periods of 62.5 and 31.25 µs, respectively), this approximation (Eq. (8)) provides STGT RDD values of 6485 µs and 3272.5 µs, respectively, which compare very well with the values determined from the 17 August measurements, shown in Table 1 under the column marked "T_{rdd}".

Only one data rate was used for the S-band Single Access (SSA) measurement on that date. However, it is known that the contribution of the Multiple Access Beamforming Equipment (MABE) to the radio frequency propagation portion of the delay is approximately 54 µs. It is also known that the SSA digital portion of the delay contains a bit period more than the MA digital portion because of the SSA baseband switch comparison process between prime and redundant data streams for routing to the MDM. Thus, taking these two facts into consideration, one would expect the formula for STGT SSA RDD to be as follows:

$$T_{rdd}\ (SSA) = 103.8T_b + 6\ \mu s \qquad (9)$$

For a 16 kbps data rate, this approximation provides an RDD value of 6493.5 µs, which also compares very well with the measured value given in the table.

The STGT-provided range propagation delays were plotted as function of time and is given as Figure 6. The smooth curve indicates that none of the range values used contained an obvious error. This was done as a “sanity check” on the measured range because the RDD results are very sensitive to errors in the range delay.

4.0 SPACECRAFT CLOCK CALIBRATION

CGRO and TOPEX each have two spacecraft clock calibration techniques available to them. CGRO has the User Spacecraft Clock Calibration System (USCCS) and the RDD technique (also called the Return Channel Time Delay technique) available. TOPEX can make use of its GPS receiver as well as the RDD technique. Both the USCCS and GPS deliver accuracy in the neighborhood of 1 µs. The RDD method is considered to be slightly less accurate, generally within about 1/4 of the telemetry data bit period, and it is sensitive to accurate knowledge of the spacecraft range to TDRS. (Prelaunch clock calibration tests of XTE in August 1995 using both the USCCS and RDD methods resulted in a difference between them (assuming an STGT RDD database value corrected by $1T_b$) which was less than 6 µs ($0.2T_b$) at 32 kbps.) CGRO generally uses the USCCS, while TOPEX generally uses the RDD method because of the often non-availability of its GPS receiver.

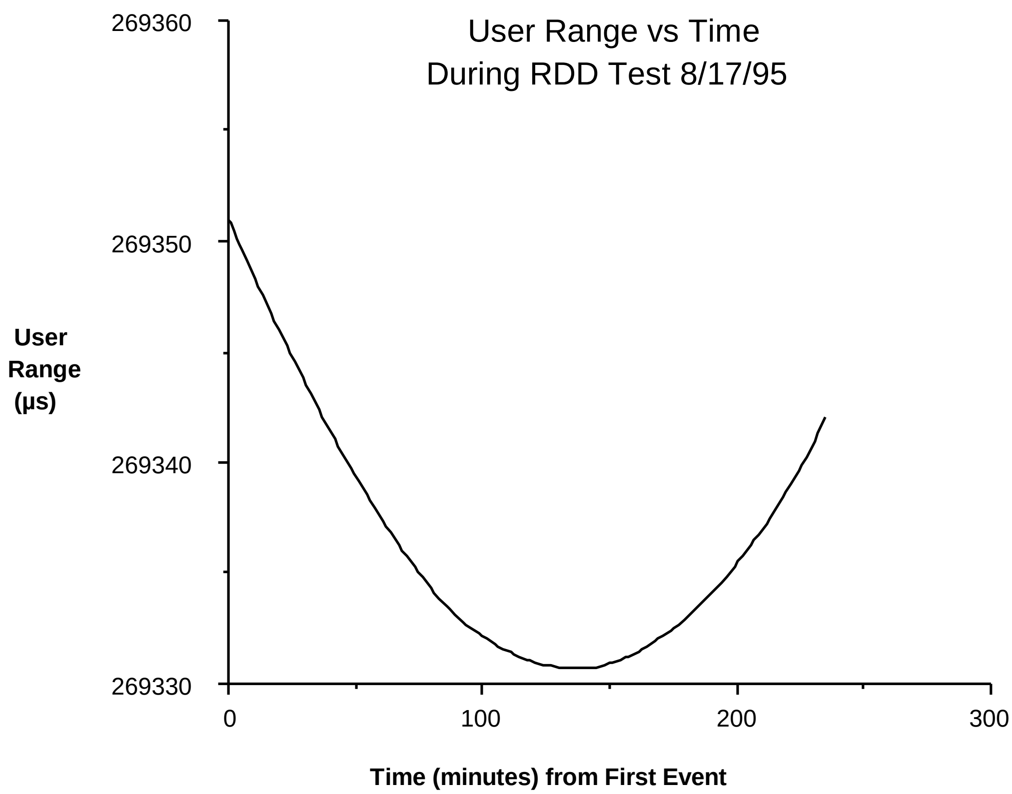

Figure 6. Range Propagation Time (8/17/95)

Since all NASA scientific spacecraft use the RDD technique either as a prime or backup method of spacecraft clock calibration, they all make a reading of their clocks at the time of creation of a particular telemetry bit. It can be assumed for the purpose of this discussion that this is the first bit of each major frame. In the case of XTE and the Tropical Rainfall Measuring Mission (TRMM), for example, the leading edge of the first bit of their 32-bit frame synchronization marker is used. The time delay between that bit and the actual clock reading is either kept to a few nanoseconds or is corrected for in the calibration. The clock value that is read is transmitted to the ground in a later portion of the telemetry stream.

There are three components in the telemetry delay prior to its being time tagged on the ground with a UTC value, which is a PB4 time based on the station atomic standard. The three are the spacecraft delay, the range delay, and the ground terminal RDD. When the spacecraft clock is accurately calibrated against UTC (~ ±1 µs) by some other method, such as GPS, the sum of the three delay components should equal the difference between the spacecraft clock reading and ground receipt time. If it does not, one of the other assumed delays is incorrect, and if the range delay can be verified, the correct ground terminal delay can thus be determined from this relationship.

In the process of determining the STGT delay, the following information was gathered:

Table 2. Spacecraft Clock Calibration Information

	CGRO	TOPEX	HST	ERBS	EUVE	XTE, TRMM	EOS-AM
RDD Technique	Yes	Yes	Yes	Yes	Yes	Yes	Yes
USCCS Technique	Yes	No	No	No	No	Yes	Yes
GPS Technique	No	Yes	No	No	No	No	
Telemetry Data Rate for Clk Calibration	32 kbps	16 kbps	4 kbps	1.6 kbps	32 kbps	32 kbps	
Data Bit Period	31.25 µs	62.5 µs	250 µs	625 µs	31.25 µs	31.25 µs	
Req'd Clk Accuracy	100 µs	100 µs	1000 µs	1000 µs			
Desired Clk Acc	10 µs	10 µs				10 µs	

5.0 RESULTS AND CONCLUSIONS

Based on an in-depth analysis of equipment delays and additional measurements, the STGT MA and SSA RDD has now been verified to be

MA: $T_{rdd} = 102.8T_b + 60\ \mu s$

SSA: $T_{rdd} = 103.8T_b + 6\ \mu s$

In addition, a one bit period RDD database error, which caused the OPM 52 messages to be too large by that amount, should be corrected by the end of 1995.

During the investigation of the possibility that the MDM might be incorrectly time tagging the data, it was discovered that there was a misadjustment of the noise window on the Data Interface System (DIS) time code generator. Other time code generators at STGT were similarly misadjusted, but they do not impact RDD. The DIS time code generator was found to cause about an 8 µs error in the PB4 time tag. After reducing the noise window, DIS testing showed that the MDM time tag is now within 1 µs of the station time standard.

Finally, the procedure for performing the GSFC end-to-end RDD measurements and the analyses involved will be applicable for verifying the WSGTU RDD. In fact, since WSGTU will be so similar to STGT, the delay values reported in this report are expected to be within a microsecond of the corresponding values at WSGTU.

It should be noted that the above effort involved data streams that were convolutionally coded and that were without periodic convolutional interleaving (PCI). This work could just as well have been done with uncoded data or with coded data and PCI without ambiguities. PCI would have merely added 1740 bit periods to the delay plus about two more bit periods for the clocking into and out of the decoder.

APPENDIX

1994 Measurements

Between July 1994 and August 1995, measurements were made of RDD at STGT for both MA and SSA services, making use of the GSFC SOC delogging software. The results of these measurements are given in Table A-1. The column marked “?” is the difference in µs between the measured delay value and that provided at that time by the OPM 52 message. The values of T_{pte} in this table, unlike Table 1, were based on the earlier incorrect formulation. As a result, the values of station delay, for the most part, were very close to the OPM 52 values.

Leading Edge vs. Mid-bit Time Tagging

It is possible that a 1/2-bit discrepancy can occur when calculating the total delay from a User spacecraft to the time tag placed on the received data by the ground terminal MDM. Because of the nature of digital circuits and their internal clocking techniques, digital time delays are generally measured from the bit leading edge. The return telemetry delay on the spacecraft is stated as a transit time through the spacecraft, just as the return telemetry delay of the ground terminal is stated as a transit time. What is meant by a transit time is the time it takes for the leading edge of a bit at some point of the system to propagate to some other point in the system. A discrepancy can arise because the leading edge of the bit is usually used as the reference in the spacecraft data system, but the data received on the ground is processed by a bit synchronizer which also generates a clock pulse whose reference transition occurs at mid-bit. The MDM then time tags the bit center, not the leading edge of the bit. This change of timing reference point may be considered a system problem, rather than a problem with the various delay measurements.

The total return delay, then, is the sum of spacecraft RDD, space propagation delay, relay satellite propagation delay, ground terminal delay, and the fraction of bit delay caused by a change of reference point. This last correction could be added to the ground terminal delay, but if it is, that information must be clearly stated or else system engineers will erroneously add it again in their analysis. Some Projects have included the timing reference point shift as part of the spacecraft delay. FH&A feels that this is a most convenient way to handle this problem and strongly recommends its use. The spacecraft delay should thus be defined as the time from when the spacecraft clock is read until the time that the middle of the reference bit reaches the spacecraft antenna.

Table A-1 1994 STGT RDD Test Results (incorrect value of PTE delay)

Day	Time	Service	Rate	Tb	Tmeas	Trng	Tpte*	Trdd	OPM 52**	Δ***	
			(Kbps)	(μs)	(μs)	(μs)	(μs)	(μs)	(μs)	(μs)	
7/20/94	16:54:23	SSA1A	32	31.25	269392	266021	92.6	3278.4	3279	0.6	* Based on Tpte=2.95 Tb
7/20/94	16:59:30	SSA1B	32	31.25	269390	266019	92.6	3278.4	3279	0.6	
7/20/94	18:36:33	SSA2A	32	31.25	269404	266032	92.6	3279.4	3279	0.6	** These OPM52 values, which
7/20/94	18:30:03	SSA2B	32	31.25	269400	266028	92.6	3279.4	3279	0.6	were within 3 ms of the actual
7/20/94	17:48:29	SSA1B	1	1000	373772	266014	2950.4	104807.6	104804	3.6	OPM52 values at that time,
7/20/94	17:44:16	SSA1A	1	1000	373772	266015	2950.4	104806.6	104804	2.6	are given by the following:
7/20/94	18:59:40	SSA2A	1	1000	373810	266049	2950.4	104810.6	104804	6.6	103.8Tb+58, MA
7/20/94	19:06:20	SSA2B	1	1000	373810	266055	2950.4	104804.6	104804	0.6	104.8Tb+4, SSA
7/20/94	15:15:26	MA3	32	31.25	269505	266111	92.6	3301.4	3301.8	0.4	***Except as noted,
7/20/94	15:34:45	MA3	32	31.25	269480	266086	92.6	3301.4	3301.8	0.4	D<0.1 TB
7/20/94	15:26:13	MA4	32	31.25	269492	266097	92.6	3302.4	3301.8	0.8	
7/20/94	16:03:20	MA3	1	1000	372892	266056	2950.4	103885.6	103858	27.6	
7/20/94	15:34:45	MA4	1	1000	372874	266086	2950.4	10.837.6	103858	20.4	
10/24/94	17:01:23	SSA2B	32	3125	269652	266282	92.6	3277.4	3279	1.6	
10/24/94	17:12:10	SSA2A	32	3125	269680	266310	92.6	3277.4	3279	1.6	
10/24/94	16:35:29	SSA1A	16	62.5	272953	266215	184.75	6553.25	6554	0.75	
10/24/94	16:42:26	SSA1B	16	62.5	272970	266233	184.75	6552.25	6554	1.75	
10/24/94	16:01:31	MA3	32	31.25	269527	266133	92.6	3301.4	3301.8	0.4	
10/24/94	15:31:37	MA3	16	62.5	272797	266067	184.75	6545.25	6545.5	0.25	
10/24/94	15:01:45	MA3	8	125	279411	266008	369.1	13033.9	13033	0.9	
10/24/94	14:31:44	MA3	4	250	292704	265957	737.9	26009.1	26008	1.1	
12/2/94	16:16:07	MA3	16	62.5	273284	266555	184.75	6544.25	6545.5	1.25	
12/2/94	15:22:46	MA3	32	31.25	269802	266407	92.6	3302.4	3301.8	0.6	
12/2/94	15:33:08	SSA	16	62.5	273143	266436	184.75	6522.25	6554	31.75(~.5Tb)	unexplained
12/2/94	15:46:55	SSA	32	31.25	269830	266474	92.6	3263.4	3279	15.6(~.5Tb)	unexplained
12/2/94	16:01:08	SSA	100	10	267594	266513	29.9	1051.1	1052	0.9	

ACRONYMS

ADPE	Automated Data Processing Equipment
ASP	ADPE Simulation Program
CGRO	Compton Gamma Ray Observatory
DIS	data interface system
EET	end-to-end test
FH&A	Fredrick Herold & Associates, Inc.
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
IOC	initial operational capability
IR	Integrated Receiver
MA	Multiple Access
MABE	MA Beamforming Equipment
MDM	mux/demux
NCC	Network Control Center
OPM	operational message
PCI	Periodic Convolutional Interleaving
PIR	Program Information Release
PMMS	Performance Measuring and Monitoring System
POCC	Project Operations Center
PTE	PMMS Test Equipment
RDD	return data delay
SGL	space-ground link
SOC	Simulations Operations Center
SSA	S-band Single Access
STGT	Second TDRS Ground Terminal
TDRS	Tracking and Data Relay Satellite
TOPEX	Tropical Ocean Mapping Experiment
TRMM	Tropical Rainfall Measuring Mission
USCCS	User Spacecraft Clock Calibration System
UTC	Universal Time Coordinated
WSGT	White Sands Ground Terminal
WSGTU	White Sands Ground Terminal Upgrade
XTE	X-Ray Timing Explorer